

¹ Fitness tracking reveals task-specific associations
² between memory, mental health, and physical activity

³ Jeremy R. Manning^{1, *}, Gina M. Notaro¹, Esme Chen¹, and Paxton C. Fitzpatrick¹

⁴ ¹Dartmouth College, Hanover, NH

⁵ *Address correspondence to jeremy.r.manning@dartmouth.edu

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Abstract

Physical activity can benefit both physical and mental well-being. Different forms of exercise (e.g., aerobic versus anaerobic; running versus walking, swimming, or yoga; high-intensity interval training versus endurance workouts; etc.) impact physical fitness in different ways. For example, running may substantially impact leg and heart strength but only moderately impact arm strength. We hypothesized that the mental benefits of physical activity might be similarly differentiated. We focused specifically on how different intensities of physical activity might relate to different aspects of memory and mental health. To test our hypothesis, we collected (in aggregate) roughly a century's worth of fitness data. We then asked participants to fill out surveys asking them to self-report on different aspects of their mental health. We also asked participants to engage in a battery of memory tasks that tested their short and long term episodic, semantic, and spatial memory performance. We found that participants with similar physical activity habits and fitness profiles tended to also exhibit similar mental health and task performance profiles. These effects were task-specific in that different physical activity patterns or fitness characteristics varied with different aspects of memory, on different tasks. Taken together, these findings provide foundational work for designing physical activity interventions that target specific components of cognitive performance and mental health by leveraging low-cost fitness tracking devices.

²⁴ Introduction

Engaging in physical activity (exercise) can improve physical fitness by increasing muscle strength [9, 20, 23, 34], bone density [1, 8, 21], cardiovascular performance [24, 32], lung capacity [22, 27] although see [35]], and endurance [43]. Physical activity can also improve mental health [2, 4, 10, 28] 12, 14, 25, 26, 27, 31, 33, 40] and cognitive performance [2, 3, 6, 11].

29 The physical benefits of exercise can be explained by stress-responses of the affected body
30 tissues. For example, skeletal muscles that are taxed during exercise exhibit stress responses [28]
31 that can in turn affect their growth or atrophy [36]. By comparison, the benefits of physical
32 activity on mental health are less direct. For example, one hypothesis is that physical activity
33 leads to specific physiological changes, such as increased aminergic synaptic transmission and

34 endorphin release, which in turn act on neurotransmitters in the brain [31]. Speculatively, if
35 different physical activity regimens lead to different neurophysiological responses, one might be
36 able to map out a spectrum of signalling and transduction pathways that are impacted by a given
37 type, duration, and intensity of physical activity in each brain region. For example, prior work has
38 shown that physical activity increases acetylcholine levels, starting in the vicinity of the exercised
39 muscles [37]. Acetylcholine is thought to play an important role in memory formation [e.g., by
40 modulating specific synaptic inputs from entorhinal cortex to the hippocampus, albeit in rodents;
41 30]. Given the central role that these medial temporal lobe structures play in memory, changes in
42 acetylcholine might lead to specific changes in memory formation and retrieval.

43 In the present study, we hypothesize that (a) different intensities of physical activity will have
44 different, quantifiable impacts on cognitive performance and mental health, and that (b) these
45 impacts will be consistent across individuals. To this end, we collected a year of real-world fitness
46 tracking data from each of 113 participants. We then asked each participant to fill out a brief survey
47 in which they self-evaluated and self-reported several aspects of their mental health. Finally, we
48 ran each participant through a battery of memory tasks, which we used to evaluate their memory
49 performance along several dimensions. We searched the data for potential associations between
50 memory, mental health, and physical activity.

51 **Methods**

52 We ran an online experiment using the Amazon Mechanical Turk (MTurk) platform [13]. We
53 collected data about each participant's fitness and physical activity habits, a variety of self-reported
54 measures concerning their mental health, and about their performance on a battery of memory
55 tasks.

56 **Experiment**

57 **Participants**

58 We recruited experimental participants by posting our experiment as a Human Intelligence Task
59 (HIT) on the MTurk platform. We limited participation to MTurk Workers who had been assigned
60 a “master worker” designation on the platform, given to workers who score highly across several
61 metrics on a large number of HITs, according to a proprietary algorithm managed by Amazon.
62 One criteria embedded into the algorithm is a requirement that master workers must maintain a
63 HIT acceptance rate of at least 95%. We further limited our participant pool to participants who
64 self-reported that they were fluent in English and regularly used a Fitbit fitness tracker device.
65 A total of 160 workers accepted our HIT in order to participate in our experiment. Of these,
66 we excluded all participants who failed to log into their Fitbit account (giving us access to their
67 anonymized fitness tracking data), encountered technical issues (e.g., by accessing the HIT using an
68 incompatible browser, device, or operating system), or who ended their participation prematurely,
69 before completing the full study. In all, 113 participants contributed usable data to the study.

70 For their participation, workers received a base payment of \$5 per hour (computed in 15
71 minute increments, rounded up to the nearest 15 minutes), plus an additional performance-based
72 bonus of up to \$5. Our recruitment procedure and study protocol were approved by Dartmouth’s
73 Committee for the Protection of Human Subjects. We obtained informed consent using an online
74 form administered to all prospective participants prior to enrolling them in our study. All methods
75 were performed in accordance with the relevant guidelines and regulations.

76 **Gender, age, and race.** Of the 113 participants who contributed usable data, 77 reported their
77 gender as female, 35 as male, and 1 chose not to report their gender. Participants ranged in age
78 from 19–68 years old (25th percentile: 28.25 years; 50th percentile: 32 years; 75th percentile: 38
79 years). Participants reported their race as White (90 participants), Black or African American (11
80 participants), Asian (7 participants), Other (4 participants), and American Indian or Alaska Native
81 (3 participants). One participant opted not to report their race.

82 **Languages.** All participants reported that they were fluent in either 1 and 2 languages (25th
83 percentile: 1; 50th percentile: 1; 75th percentile: 1), and that they were “familiar” with between 1
84 and 11 languages (25th percentile: 1; 50th percentile: 2; 75th percentile: 3).

85 **Reported medical conditions and medications.** Participants reported having and/or taking med-
86 ications pertaining to the following medical conditions: anxiety or depression (4 participants),
87 recent head injury (2 participants), high blood pressure (1 participant), bipolar disorder (1 partici-
88 pant), hypothyroidism (1 participant), and other unspecified conditions or medications (1 partici-
89 pant). Participants reported their current and typical stress levels on a Likert scale as very relaxed
90 (-2), a little relaxed (-1), neutral (0), a little stressed (1), or very stressed (2). The “current” stress
91 level reflected participants’ stress at the time they participated in the experiment. Their responses
92 ranged from -2 to 2 (current stress: 25th percentile: -2; 50th percentile: -1; 75th percentile: 1; typical
93 stress: 25th percentile: 0; 50th percentile: 1; 75th percentile: 1). Participants also reported their
94 current level of alertness on a Likert scale as very sluggish (-2), a little sluggish (-1), neutral (0), a
95 little alert (1), or very alert (2). Their responses ranged from -2 to 2 (25th percentile: 0; 50th per-
96 centile: 1; 75th percentile: 2). Nearly all (111 out of 113) participants reported that they had normal
97 color vision, and 15 participants reported uncorrected visual impairments (including dyslexia and
98 uncorrected near- or far-sightedness).

99 **Residence and level of education.** Participants reported their residence as being located in the
100 suburbs (36 participants), a large city (30 participants), a small city (23 participants), rural (14 partic-
101 ipants), or a small town (10 participants). Participants reported their level of education as follows:
102 College graduate (42 participants), Master’s degree (23 participants), Some college (21 partici-
103 pants), High school graduate (9 participants), Associate’s degree (8 participants), Other graduate
104 or professional school (5 participants), Some graduate training (3 participants), or Doctorate (2
105 participants).

106 **Reported water and coffee intake.** Participants reported the number of 8 oz cups of water and
107 coffee they had consumed prior to accepting the HIT. Water consumption ranged from 0–6 cups

¹⁰⁸ (25th percentile: 1; 50th percentile: 3; 75th percentile: 4). Coffee consumption ranged from 0–4 cups
¹⁰⁹ (25th percentile: 0; 50th percentile: 1; 75th percentile: 2).

¹¹⁰ **Tasks**

¹¹¹ Upon accepting the HIT posted on MTurk, each worker was directed to read and fill out a screening
¹¹² and consent form, and to share access to their anonymized Fitbit data via their Fitbit account. After
¹¹³ consenting to participate in our study and successfully sharing their Fitbit data, participants filled
¹¹⁴ out a survey and then engaged in a series of memory tasks (Fig. 1). All stimuli and code for running
¹¹⁵ the full MTurk experiment may be found [here](#).

¹¹⁶ **Survey questions.** We collected the following demographic information from each participant:
¹¹⁷ their birth year, gender, highest (academic) degree achieved, race, language fluency, and language
¹¹⁸ familiarity. We also collected information about participants' health and wellness, including about
¹¹⁹ their vision, alertness, stress, sleep, coffee and water consumption, location of their residence,
¹²⁰ activity typically required for their job, and physical activity habits.

¹²¹ **Free recall (Fig. 1a).** Participants studied a sequence of four word lists, each comprising 16 words.
¹²² After studying each list, participants received an immediate memory test, whereby they were asked
¹²³ to type (one word at a time) any words they remembered from the just-studied list, in any order.

¹²⁴ Words were presented for 2 s each, in black text on a white background, followed by a 2 s blank
¹²⁵ (white) screen. After the final 2 s pause, participants were given 90 s to type in as many words
¹²⁶ as they could remember, in any order. The memory test was constructed such that the participant
¹²⁷ could only see the text of the current word they were typing; when they pressed any non-letter
¹²⁸ key, the current word was submitted and the text box they were typing in was cleared. This was
¹²⁹ intended to prevent participants from retroactively editing their previous responses.

¹³⁰ The word lists participants studied were drawn from the categorized lists reported by [44]. Each
¹³¹ participant was assigned four unique randomly chosen lists (in a randomized order), selected from
¹³² a full set of 16 lists. Each chosen list was then randomly shuffled before presenting the words to

Main task and immediate memory test					Delayed memory test
a.	1	<p>Free recall</p> <p>Study words</p> <p>16 words per list</p> <p>4 lists</p>	<p>Memory test</p> <p>Please type each word you remember into the prompt:</p> <input type="text"/>	5	
b.	2	<p>Naturalistic recall</p> <p>Watch a short video (The Temple of Knowledge)</p> <p>Video clip plays</p>	<p>Memory tests</p> <p>Please type anything you remember about what happened in the video you watched:</p> <input type="text"/> <p>Ronald's favorite activity was:</p> <ul style="list-style-type: none"> <input type="radio"/> coding <input type="radio"/> reading <input type="radio"/> piano <input type="radio"/> running 	6	
c.	3	<p>Foreign language flashcards</p>	<p>Memory test</p> <p>Multiple choice</p>	7	
d.	4	<p>Spatial learning</p> <p>Memorize the positions of increasing numbers of shapes</p>			N/A

Figure 1: Battery of memory tasks. **a. Free recall.** Participants study 16 words (presented one at a time), followed by an immediate memory test where they type each word they remember from the just-studied list. In the delayed memory test, participants type any words they remember studying, from any list. **b. Naturalistic recall.** Participants watch a brief video, followed by two immediate memory tests. The first test asks participants to write out what happened in the video. The second test has participants answer a series of multiple choice questions about the conceptual content of the video. In the delayed memory test, participants (again) write out what happened in the video. **c. Foreign language flashcards.** Participants study a sequence of 10 English-Gaelic word pairs, each presented with an illustration of the given word. During an immediate memory test, participants perform a multiple choice test where they select the Gaelic word that corresponds to the given photograph. During the delayed memory test, participants perform a second multiple choice test, where they select the Gaelic word that corresponds to each of a new set of photographs. **d. Spatial learning.** In each trial, participants study a set of randomly positioned shapes. Next, the shapes' positions are altered, and participants are asked to drag the shapes back to their previous positions. **All panels.** The gray numbers denote the order in which participants experienced each task or test.

¹³³ the participants. Participants also performed a final delayed memory test where they were given
¹³⁴ 180 s to type out any words they remembered from *any* of the 4 lists they had studied.

¹³⁵ Recalled words within an edit distance of 2 (i.e., a Levenshtein Distance less than or equal to
¹³⁶ 2) of any word in the wordpool were “autocorrected” to their nearest match. We also manually
¹³⁷ corrected clear typos or misspellings by hand (e.g., we corrected “hippoptumas” to “hippopota-
¹³⁸ mus”, “zucinni” to “zucchini”, and so on). Finally, we lemmatized each submitted word to match
¹³⁹ the plurality of the matching wordpool word (e.g., “bongo” was corrected to “bongos”, and so
¹⁴⁰ on). After applying these corrections, any submitted words that matched words presented on the
¹⁴¹ just-studied list were tagged as “correct” recalls, and any non-matching words were discarded
¹⁴² as “errors.” Because participants were not allowed to edit the text they entered, we chose not to
¹⁴³ analyze these putative “errors,” since we could not distinguish typos from true misrememberings.

¹⁴⁴ **Naturalistic recall (Fig. 1b).** Participants watched a 2.5 minute video clip entitled “The Temple
¹⁴⁵ of Knowledge.” The video comprises an animated story told to StoryCorps by Ronald Clark, who
¹⁴⁶ was interviewed by his daughter, Jamilah Clark. The narrator (Ronald) discusses growing up
¹⁴⁷ living in an apartment over the Washington Heights branch of the New York Public Library, where
¹⁴⁸ his father worked as a custodian during the 1940s.

¹⁴⁹ After watching the video clip, participants were asked to type out anything they remembered
¹⁵⁰ about what happened in the video. They typed their responses into a text box, one sentence at a
¹⁵¹ time. When the participant pressed the return key or typed any final punctuation mark (“.”, “!”, or
¹⁵² “?”) the text currently entered into the box was “submitted” and added to their transcript, and the
¹⁵³ text box was cleared to prevent further editing of any already-submitted text. This was intended to
¹⁵⁴ prevent participants from retroactively editing their previous responses. Participants were given
¹⁵⁵ up to 10 minutes to enter their responses. After 4 minutes, participants were given the option of
¹⁵⁶ ending the response period early, e.g., if they felt they had finished entering all of the information
¹⁵⁷ they remembered. Each participant’s transcript was constructed from their submitted responses by
¹⁵⁸ combining the sentences into a single document and removing extraneous whitespace characters.
¹⁵⁹ Following this 4–10 minute free response period, participants were given a series of 10 multiple

¹⁶⁰ choice questions about the conceptual content of the story. All participants received the same
¹⁶¹ questions, in the same order. Participants also performed a final delayed memory test, where they
¹⁶² carried out the free response recall task a second time, near the end of the testing session. This
¹⁶³ resulted in a second transcript, for each participant.

¹⁶⁴ **Foreign language flashcards (Fig. 1c).** Participants studied a series of 10 English-Gaelic word
¹⁶⁵ pairs in a randomized order. We selected the Gaelic language both for its relatively small number
¹⁶⁶ of native speakers and for its dissimilarity to other commonly spoken languages amongst MTurk
¹⁶⁷ workers. We verified (via self report) that all of our participants were fluent in English and that
¹⁶⁸ they were neither fluent nor familiar with Gaelic.

¹⁶⁹ Each word's "flashcard" comprised a cartoon depicting the given word, the English word or
¹⁷⁰ phrase in lowercase text (e.g., "the boy"), and the Gaelic word or phrase in uppercase text (e.g.,
¹⁷¹ "BUACHAILL"). Each flashcard was displayed for 4 s, followed by a 3 s interval (during which
¹⁷² the screen was cleared) prior to the next flashcard presentation.

¹⁷³ After studying all 10 flashcards, participants were given a multiple choice memory test where
¹⁷⁴ they were shown a series of novel photographs, each depicting one of the 10 words they had
¹⁷⁵ learned. They were asked to select which (of 4 unique options) Gaelic word went with the given
¹⁷⁶ picture. The 3 incorrect options were selected at random (with replacement across trials), and the
¹⁷⁷ order in which the choices appeared to the participant were also randomized. Each of the 10 words
¹⁷⁸ they had learned were tested exactly once.

¹⁷⁹ Participants also performed a final delayed memory test, where they were given a second set of
¹⁸⁰ 10 questions (again, one per word they had studied). For this second set of questions participants
¹⁸¹ were prompted with a new set of novel photographs, and new randomly chosen incorrect choices
¹⁸² for each question. Each of the 10 original words they had learned were (again) tested exactly once
¹⁸³ during this final memory test.

¹⁸⁴ **Spatial learning (Fig. 1d).** Participants performed a series of study-test trials where they memo-
¹⁸⁵ rized the onscreen spatial locations of two or more shapes. During the study phase of each trial,

186 a set of shapes appeared on the screen for 10 s, followed by 2 s of blank (white) screen. During the
187 test phase of each trial, the same shapes appeared onscreen again, but this time they were vertically
188 aligned and sorted horizontally in a random order. Participants were instructed to drag (using the
189 mouse) each shape to its studied position, and then to click a button to indicate that the placements
190 were complete.

191 In different study-test trials, participants learned the locations of different numbers of shapes
192 (always drawn from the same pool of 7 unique shapes, where each shape appeared at most one
193 time per trial). They first performed three trials where they learned the locations of 2 shapes; next
194 three trials where they learned the locations of 3 shapes; and so on until their last three trials, where
195 (during each trial) they learned the locations of 7 shapes. All told, each participant performed 18
196 study-test trials of this spatial learning task (3 trials for each of 2, 3, 4, 5, 6, and 7 shapes).

197 **Fitness tracking using Fitbit devices**

198 To gain access to our study, participants provided us with access to all data associated with their
199 Fitbit account from the year (365 calendar days) up to and including the day they accepted the HIT.
200 We filtered out all identifiable information (e.g., participant names, GPS coordinates, etc.) prior to
201 importing their data.

202 **Collecting and processing Fitbit data**

203 The fitness tracking data associated with participants' Fitbit accounts varied in scope and duration
204 according to which device the participant owned (Fig. S1), how often the participant wore (and/or
205 synced) their tracking device, and how long they had owned their device. For example, while all
206 participants' devices supported basic activity metrics such as daily step counts, only a subset of
207 the devices with heart rate monitoring capabilities provided information about workout intensity,
208 resting heart rate, and other related measures. Across all devices, we collected the following infor-
209 mation: heart rate data, sleep tracking data, logged bodyweight measurements, logged nutrition
210 measurements, Fitbit account and device settings, and activity metrics.

211 **Heart rate.** If available, we extracted all heart rate data collected by participants' Fitbit device(s)
212 and associated with their Fitbit profile. Depending on the specific device model(s) and settings, this
213 included second-by-second, minute-by-minute, daily summary, weekly summary, and/or monthly
214 summary heart rate information. These summaries include information about participants' aver-
215 age heart rates, and the amount of time they were estimated to have spent in different "heart rate
216 zones" (rest, out-of-range, fat burn, cardio, or peak, as defined by their Fitbit profile), as well as an
217 estimate of the number of estimated calories burned while in each heart rate zone.

218 **Sleep.** If available, we extracted all sleep data collected by participants' Fitbit device(s). Depend-
219 ing on the specific device model(s) and settings, this included nightly estimates of the duration
220 and quality of sleep, as well as the amount of time spent in each sleep stage (awake, REM, light, or
221 deep).

222 **Weight.** If available, we extracted any weight-related information affiliated with participants'
223 Fitbit accounts within 1 year prior to enrolling in our study. Depending on their specific device
224 model(s) and settings, this included their weight, body mass index, and/or body fat percentage.

225 **Nutrition.** If available, we extracted any nutrition-related information affiliated with participants'
226 Fitbit accounts within 1 year prior to enrolling in our study. Depending on their specific account
227 settings and usage behaviors, this included a log of the specific foods they had eaten (and logged)
228 over the past year, and the amount of water consumed (and logged) each day.

229 **Account and device settings.** We extracted any settings associated with participants' Fitbit ac-
230 counts to determine (a) which device(s) and model(s) are associated with their Fitbit account, (b)
231 time(s) when their device(s) were last synced, and (c) battery level(s).

232 **Activity metrics.** If available, we extracted any activity-related information affiliated with par-
233 ticipants' Fitbit accounts within 1 year prior to enrolling in our study. Depending on their specific
234 device model(s) and settings, this included: daily step counts; daily amount of time spent in each

235 activity level (sedentary, lightly active, fairly active, or very active, as defined by their account
236 settings and preferences); daily number of floors climbed; daily elevation change; and daily total
237 distance traveled.

238 **Comparing recent versus baseline measurements.**

239 We were interested in separating out potential associations between *absolute* fitness metrics and
240 *relative* metrics. To this end, in addition to assessing potential raw (absolute) fitness metrics, we
241 also defined a simple measure of recent changes in those metrics, relative to a baseline:

$$\Delta_{R,B}m = \frac{B \sum_{i=1}^R m(i)}{R \sum_{i=R+1}^{R+B} m(i)},$$

242 where $m(i)$ is the value of metric m from $i - 1$ days prior to testing (e.g., $m(1)$ represents the value
243 of m on the day the participant accepted the HIT, and $m(10)$ represents the value of m 9 days prior
244 to accepting the HIT. We set $R = 7$ and $B = 30$. In other words, to estimate recent changes in any
245 metric m , we divided the average value of m taken over the prior week by the average value of m
246 taken over the 30 days before that.

247 **Exploratory correlation analyses**

248 We used a bootstrap procedure to identify reliable correlations between different memory-related,
249 fitness-related, and demographic-related variables. For each of $N = 10,000$ iterations, we selected
250 (with replacement) a sample of 113 participants to include. This yielded, for each iteration, a
251 sampled “data matrix” with one row per sampled participant and one column for each measured
252 variable. When participants were sampled multiple times in a given iteration, as was often the
253 case, this matrix contained duplicate rows. Next, we computed the Pearson’s correlation between
254 each pair of columns. This yielded, for each pair of columns, a distribution of N bootstrapped
255 correlation coefficients. If 97.5% or fewer of the coefficients for a given pair of columns had the
256 same sign, we excluded the pair from further analysis and considered the expected correlation
257 between those columns to be undefined. If > 97.5% of the coefficients for a given pair of columns

had the same sign (corresponding to a bootstrap-estimated two-tailed p threshold of 0.05), we computed the expected correlation coefficient as:

$$\mathbb{E}_{i,j}[r] = \tanh\left(\frac{1}{N} \sum_{n=1}^N \tanh^{-1}(\text{corr}(m(i)_n, m(j)_n))\right),$$

where $m(x)_n$ represents column x of the bootstrapped data matrix for iteration n , \tanh is the hyperbolic tangent, and \tanh^{-1} is the inverse hyperbolic tangent. We estimated the corresponding p -values for these correlations as one minus the proportion of bootstrapped correlations with the same sign, multiplied by two.

Reverse correlation analyses

We sought to characterize potential associations between the *dynamics* of participants' fitness-related activities leading up to the time they participated in a memory task and their performance on the given task. For each fitness-related variable, we constructed a timeseries matrix whose rows corresponded to timepoints (sampled once per day) leading up to the day the participant accepted the HIT for our study, and whose columns corresponded to different participants. These matrices often contained missing entries, since different participants' Fitbit devices tracked fitness-related activities differently. For example, participants whose Fitbit devices lacked heart rate sensors would have missing entries for any heart rate-related variables. Or, if a given participant neglected to wear their fitness tracker on a particular day, the column corresponding to that participant would have missing entries for that day. To create stable estimates, we smoothed the timeseries of each fitness measure using a sliding window of 1 week. In other words, for each fitness measure, we replaced the "observed value" for each day with the average values of that measure (when available) over the 7 day interval ending on the given day.

In addition to this set of matrices storing timeseries data for each fitness-related variable, we also constructed a memory performance matrix, M , whose rows corresponded to different memory-related variables, and whose columns corresponded to different participants. For example, one row of the memory performance matrix reflected the average proportion of words (across lists)

282 that each participant remembered during the immediate free recall test, and so on.

283 Given a fitness timeseries matrix, F , we computed the weighted average and weighted standard
284 error of the mean of each row of F , where the weights were given by a particular memory-related
285 variable (row of M). For example, if F contained participants' daily step counts, we could use
286 any row of M to compute a weighted average across any participants who contributed step count
287 data on each day. Choosing a row of M that corresponded to participants' performance on the
288 naturalistic recall task would mean that participants who performed better on the naturalistic recall
289 task would contribute more to the weighted average timeseries of daily step counts. Specifically,
290 for each row, t , of F , we computed the weighted average (across the S participants) as:

$$\bar{f}(t) = \sum_{s=1}^S \hat{m}(s)F(t,s),$$

291 where \hat{m} denotes the normalized min-max scaling of m (the row of M corresponding to the chosen
292 memory-related variable):

$$\hat{m} = \frac{m}{\sum_{s=1}^S \hat{m}(s)},$$

293 where

$$\hat{m} = (1 - \epsilon) \frac{m - \min(m)}{\max(m) - \min(m)} + \epsilon.$$

294 Here, ϵ provides a lower bound on the influence of the lowest-weighted participant's data. We
295 defined $\epsilon = 0.001$, ensuring that the lowest-weighted participant had relatively low (but non-zero)
296 influence. We computed the weighted standard error of the mean as:

$$\text{SEM}_m(f(t)) = \frac{\left| \sum_{s=1}^S (F(t,s) - \bar{f}(t)) \right|}{\sqrt{S}}.$$

297 When a given row of F was missing data from one or more participants, those participants were
298 excluded from the weighted average for the corresponding timepoint and the weights (across all
299 remaining participants) were re-normalized to sum to 1. The above procedure yielded, for each
300 memory variable, a timeseries of weighted average (and weighted standard error of the mean)

301 fitness tracking values leading up to the day of the experiment.

302 **Results**

303 Before testing our main hypotheses, we examined the behavioral data from each of four memory
304 tasks: a random word list learning “free recall” task (Fig. 1); a naturalistic recall task whereby par-
305 ticipants watched a short video and then recounted the narrative; a foreign language “flashcards”
306 task; and a spatial learning task. Each of the first three tasks (free recall, naturalistic recall, and the
307 flashcards task) included both an immediate (short term) memory test and a delayed (long term)
308 memory test. The spatial learning task included only an immediate test. Participants in all four
309 tasks exhibited general trends and tendencies that have been previously reported in prior work.
310 We were also interested in characterizing the variability in task performance across participants.
311 For example, if all participants exhibited near-identical behaviors or performance on a given task,
312 we would be unable to identify how memory performance on that task varied with mental health
313 or physical activity.

314 When participants engaged in free recall of random word lists, they displayed strong primacy
315 and recency effects [29] on the immediate memory tests (as reflected by improved memory for
316 early and late list items; Fig. 2a, left and right panels). On the delayed memory test, the recency
317 effect was substantially diminished (Fig. 3a, left and right panels), consistent with myriad previous
318 studies [for review see 18]. Participants also tended to cluster their recalls according to the words'
319 study positions [17] on both the immediate (Fig. 2a, middle panel) and delayed (Fig. 3a, middle
320 panel) memory tests.

321 When participants engaged in naturalistic recall by recounting the narrative of a short story
322 video, they reliably and accurately remembered the major narrative events on both the immediate
323 (Fig. 2b) and delayed (Fig. 3b) tests. This is consistent with prior work showing that memory for
324 rich narratives is both detailed and accurate [7, 15].

325 Performance on the foreign language flashcards task (immediate: Fig. 2c; delayed: Fig. 3c)
326 varied substantially across participants, and did not show any clear serial position effects. Partic-

327 ipants also displayed substantial variation in performance on the spatial learning task (Fig. 2d).
328 In general, participants reported the shape's positions more accurately when there were fewer
329 shapes. However, both the baseline estimation accuracy and the rate of decrease in accuracy as a
330 function of increasing number of memorized locations varied substantially across participants.

331 In addition to observing substantial across-participant variability in memory performance,
332 we also observed substantial variability in participants' fitness and activity metrics (Fig. 4). We
333 examined recent measurements, averaged over the week prior to testing (Fig. 4a), baselined mea-
334 surements (average over the prior week, divided by the average over the preceding 30 days;
335 Fig. 4b), along with more gradually varying measures that tended to remain relatively static over
336 timescales of weeks to months (Fig. 4c). Figure S6 displays across-participant distributions for
337 a broad selection of these measures, and Figures S7, S8, S9, and S10 show different participants'
338 fitness metrics, broken down by their performance on different memory tasks.

339 We wondered about potential links between the different aspects of participants' data. For
340 example, if people who engaged in particular intensities of physical activity also tended to per-
341 form better on a given memory task, this could suggest that either (a) some property intrinsic to
342 participants who exercised in a particular way might also affect their memory performance on the
343 given task, and/or (b) particular physical activity behaviors could have a causal impact on memory
344 performance. We carried out an exploratory analysis whereby we used a bootstrap-based approach
345 to identify reliable correlations between different aspects of memory performance (Fig. S11), dif-
346 ferent aspects of fitness (Fig. S12), different demographic attributes (Fig. S13), and correlations
347 between memory performance, fitness information, and demographic attributes (Fig. S14). Specif-
348 ically, we sought to identify correlations that were present in the same direction (i.e., positive or
349 negative) across different subsets of participants. For each test, we report the average correlation
350 (taken across 10,000 subsets of participants, chosen with replacement) and an associated two-tailed
351 p -value, estimated as

$$p = 2 \times (1 - q),$$

352 where q is the proportion of those 10,000 subsets that exhibited correlations in the same direction

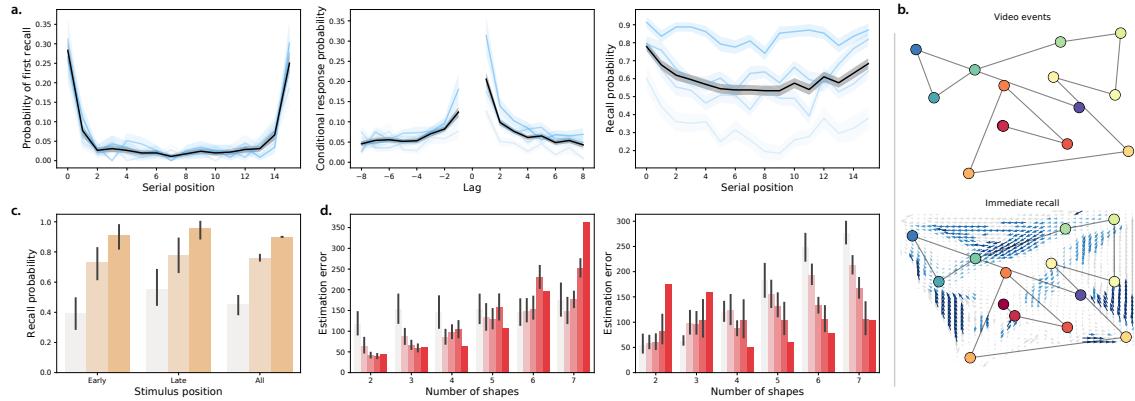


Figure 2: Immediate memory tests. **a. Free recall.** Left: probability of recalling each word first as a function of its presentation position. Middle: probability of transitioning between successively recalling the word presented at position i , followed by word presented at position $i + \text{Lag}$. Right: probability of recalling each word as a function of its presentation position. See Figure S2 for additional details. **b. Naturalistic recall.** Top: 2D embedding of a 2.5 min video clip; each dot reflects a narrative event (red denotes early events and blue denotes later events). Bottom: 2D embedding of the averaged transcripts of participants' recounts of the narrative (dots: same format as top panel). The arrows denote the average trajectory directions through the corresponding region of text embedding space, for any participants whose recounts passed through that region. Blue arrows denote statistically reliable agreement across participants ($p < 0.05$, corrected). See Figure S3 for additional details. **c. Foreign language flashcards.** Each bar denotes the average proportion of correctly recalled Gaelic-English word pairs from early (first 3), late (last 3), or all (i.e., all 10) study positions. See Figure S4 for additional details. **d. Spatial learning.** Average estimation error in shape locations as a function of the number of shapes. See Figure S5 for additional details. All panels: error bars and error ribbons denote bootstrap-estimated 95% confidence intervals. Shading (saturation) denotes results for different subsets of participants assigned based on their task performance (Figs. S2, S3, S4, and S5 provide information about which performance metrics and values the shading reflects; in general more saturated colors denote participants who performed better on the given task.) In Panel d, participants are grouped in two ways; in the left panel, participants are grouped according to the y -intercepts of regression lines (estimation error as a function of the number of shapes); in the right panel, participants are grouped according to the slopes of the same regression lines.

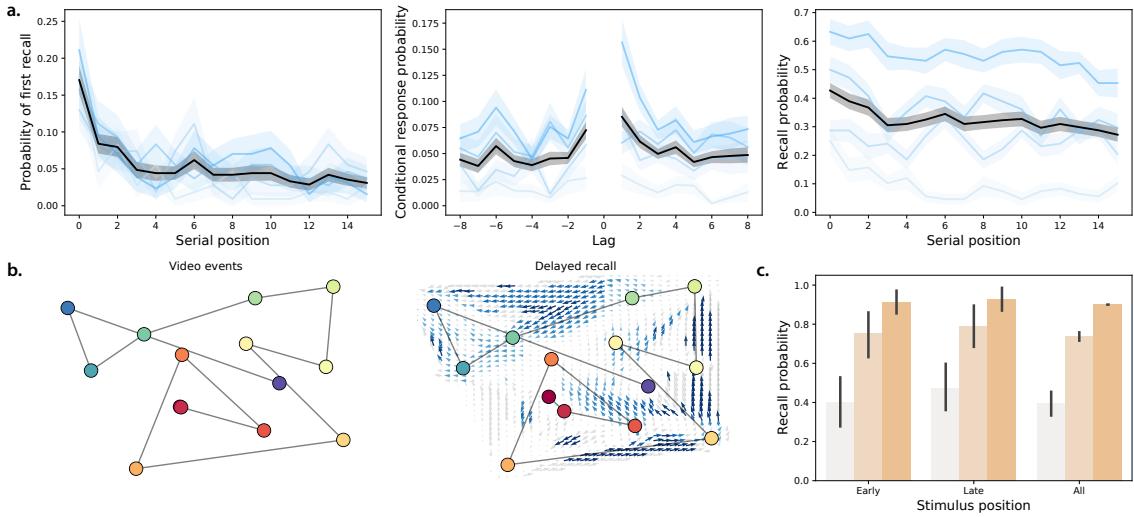


Figure 3: Delayed memory tests. **a. Free recall.** These panels are in the same format as Figure 2a, but they reflect performance on the delayed free recall task. For additional details see Figure S2. **b. Naturalistic recall.** These panels are in the same format as Figure 2b, but the right panel reflects performance on the delayed naturalistic recall task. For additional details see Figure S3. **c. Foreign language flashcards.** This panel is in the same format as Figure 2c, but it reflects performance on the delayed flashcards test. For additional details see Figure S4.

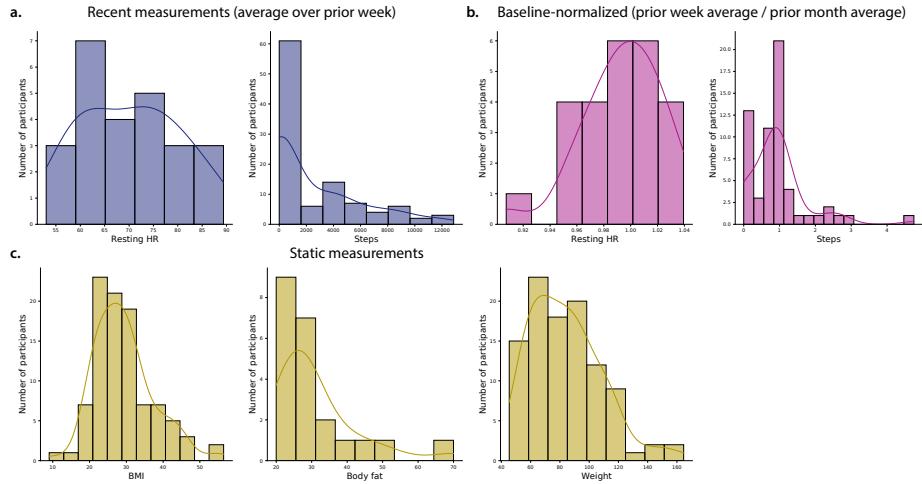


Figure 4: Fitness measures. **a. Recent measures.** Resting heart rate (HR) and daily step counts, averaged over the week prior to testing. **Baseline-normalized measures.** Resting heart rate and daily step counts averaged over the week prior to testing, divided by the average resting heart rate and step counts averaged over the preceding month. **Static measures.** Body mass index (BMI), body fat percentage, and weight (in kg). For more information see Figures S6, S7, S8, S9, and S10.

353 (see *Exploratory correlation analyses*). When all 10,000 randomly chosen subsets of participants ex-
354 hibited correlations in the same direction (i.e., all positive correlations or all negative correlations),
355 we report the p -value as $p < 0.0001$.

356 Several patterns emerged from these analyses. First, we found that participants' performance
357 on the (within-task) immediate versus delayed memory tests from the free recall, naturalistic
358 recall, and foreign language flashcards tasks were positively correlated ($rs > 0.25, ps < 0.003$).
359 This suggests that, within each of these tasks, similar processes or constraints may influence both
360 short term and long term information retrieval. We also found reliable across-task correlations
361 between participants' (immediate and delayed) performance on the free recall and foreign language
362 flashcards tasks ($rs > 0.3, ps < 0.03$).

363 A large number of fitness-related measures displayed reliable correlations (for a complete re-
364 port, see Fig. S12). For example, body mass index (BMI) and weight were correlated ($r = 0.91, p <$
365 0.0001). Resting heart rate over the prior week was negatively correlated with recent low-to-
366 moderate-intensity ("fat burn") cardiovascular activity levels ($r = 0.70, p = 0.0004$). Participants'
367 peak heart rates (averaged over the prior week) were also negatively correlated with recent in-
368 creases in step counts and daily elevation gains ($rs < -0.26, ps < 0.03$), where recent changes
369 were defined as the average values over the seven days leading up to the test day divided by
370 the average values over the preceding 30 days. Several demographic attributes (Fig. S13) dis-
371 played trivial correlations (e.g., participants identifying as male never reported identifying as
372 female, and so on). We also observed a negative correlation between reported stress and alertness
373 ($r = -0.44, p < 0.0001$), and positive correlations between the reported clarity of the instructions
374 for all tasks ($rs > 0.26, ps < 0.02$).

375 We also found reliable correlations between participants' fitness and demographic measures
376 and their behaviors in different tasks (for a complete report, see Fig. S14). For example, recent
377 low-to-moderate-intensity ("fat burn") cardiovascular activity was positively correlated with im-
378 mediate ($r = 0.38, p = 0.03$) and delayed ($r = 0.38, p = 0.029$) recall performance on the naturalistic
379 memory task. Recent increases in moderate-intensity ("cardio") activity over the prior 7 days
380 (relative to the preceding 30 days) was also positively correlated with immediate naturalistic re-

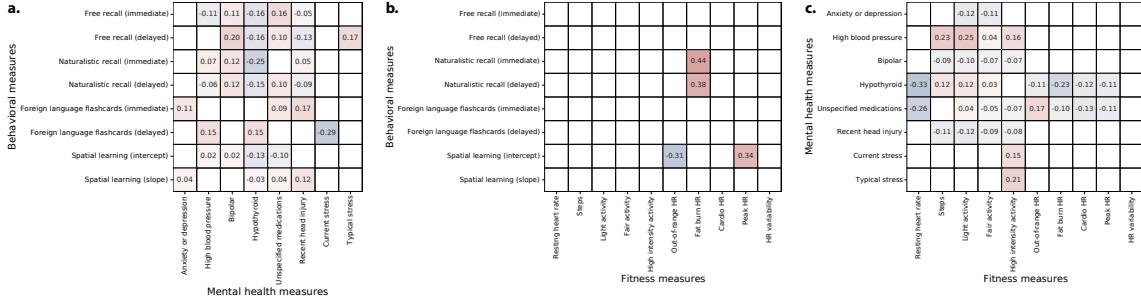


Figure 5: Summaries of correlations between behavioral, fitness, and mental health measures. The reported values in the tables reflect correlations between each behavioral measure and mental health measure. Only statistically reliable correlations ($p < 0.05$, corrected) are displayed. **a. Correlations between behavioral and mental health measures.** We adjusted each task's behavioral measure(s) such that more positive values reflect better performance on the given task. We used participants' mean recall accuracy to characterize performance on the free recall and foreign language flashcards tasks, and mean precision to characterize performance on the naturalistic recall tasks. We characterized performance on the spatial learning task using the (inverted and normalized) intercepts and slopes of linear regressions on mean estimation errors as a function of the number of studied shapes (also see Figs. 2, 3, S2, S3, S4, and S5). For each mental health measure, more positive values denote greater severity of the given measure. Typical and current stress levels were measured by self report. Mental health information was inferred using each participants' list of self-reported medications (see *Methods*). Positive correlations indicate that better performance on a given behavioral task is associated with more severe mental health phenotypes. **b. Correlations between fitness and mental health measures.** For each fitness measure, more positive values denote higher observed scores (i.e., higher resting heart rate, more minutes of activity or time spent in each heart rate zone, or greater heart rate variability). The mental health measures in this panel were treated as in Panel a. **c. Correlations between fitness and behavioral measures.** Each measure reflected in this panel was treated as in Panels a and b.

381 call performance ($r = 0.48, p = 0.003$) and immediate recall performance on the foreign language
382 flashcards task ($r = 0.43, p = 0.048$). Recent high-intensity (“peak”) activity was positively corre-
383 lated with performance on the spatial learning task ($r = 0.34, p < 0.0001$), as were recent increases
384 in high-intensity activity (prior 7 days versus preceding 30 days; $r = 0.41, p = 0.01$). Mental
385 health indicators, such as self-reported stress levels and medications were also associated with
386 differences in memory (Figs. 5, S14). For example, self-reported stress levels at the time of test
387 were negatively correlated with performance on the delayed memory test for the foreign language
388 flashcards task ($r = -0.29, p = 0.038$), whereas participants who were medicated for anxiety and
389 depression tended to perform slightly (but reliably) *better* on the immediate memory test for the
390 foreign language flashcards task ($r = 0.11, p < 0.0001$).

391 The above analyses indicate that recent differences in fitness-related activity are associated with
392 differences in memory performance and mental health measures. Although the analyses treated
393 these measures on average or in aggregate, many of the measures we collected are dynamic. For
394 example, the amount or intensity of physical activity people engage in can vary over time, and
395 so on. We wondered whether the dynamics of fitness-related measures might relate to memory
396 performance and/or mental health measures. To this end, we carried out a series of reverse
397 correlation analyses (see *Reverse correlation analyses*) to examine whether participants with different
398 cognitive or mental health profiles also tended to display differences in fitness-related measures
399 over time. In particular, we examined fitness data collected from participants’ Fitbit devices over the
400 year prior to their test day in our study. Several example findings are summarized in Figure 6. We
401 found that participants who performed well on the immediate and delayed free recall memory tests
402 and on the naturalistic recall tests tended to be more active than participants who performed poorly
403 on those tests (Figs. 6a, b; S15). Conversely, participants who performed well on the immediate
404 and delayed foreign language flashcards tasks tended to be *less* active. These differences were
405 present even a full year before the testing day. We also found substantial variability across people
406 with different (self-reported) mental health profiles (Figs. 6c, S18). Due to small sample sizes of
407 individuals exhibiting several mental health dimensions, it is difficult to distinguish generalizable
408 trends from individual differences that one or two individuals happened to exhibit. However,

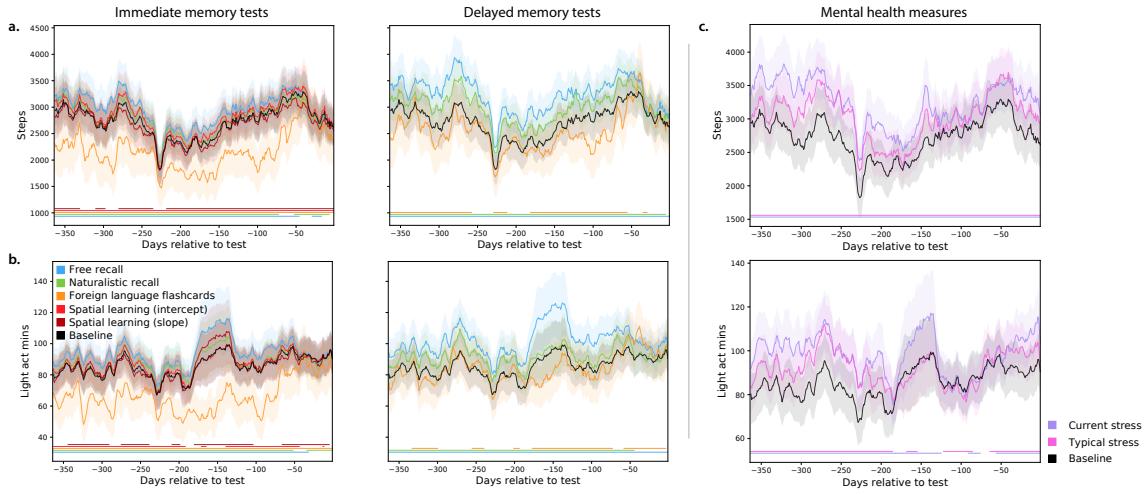


Figure 6: Dynamics of physical activity varies with memory performance and mental health measures. **a. Daily step counts.** Each timecourse is weighted by either performance on immediate recall tests (left panel) or on delayed recall tests (right panel). The black (baseline) timecourses display the (unweighted) average across all participants. **b. Daily duration (in minutes) of low-intensity physical activity.** Timecourses are displayed in the same format and color scheme as those in Panel A. Analogous timecourses for additional fitness-related measures may be found in Figures S15, S16, and S17. **c. Timecourses of physical activity, weighted by mental health measures.** The timecourses in each panel display the average daily step counts (top panel) or duration of low-intensity activity (bottom panel). The colored lines show average activity dynamics weighted by self-reported stress levels at the start of the experiment (purple) and self-reported “typical” stress levels (pink). The baseline curves (black) display the average across all participants (re-plotted in Panel C to illustrate scale differences across panels). Timecourses for additional mental health-related and fitness-related measures may be found in Figures S18, S19, and S20. Error ribbons in all panels denote the standard error of the mean. Horizontal lines below each panel’s timecourses denote intervals over which each weighted measure (color) differs from the unweighted baseline (via a paired sample two-sided t -test of the weighted mean values for each measure within a 30 day window around each timepoint; horizontal lines denote $p < 0.05$, corrected).

409 several large-sample-size trends emerged. For example, participants who reported higher levels
410 of stress also tended to be slightly more physically active than participants who reported lower
411 stress levels. We found analogous differences in other activity-related measures (Figs. S15 and S18),
412 cardiovascular measures (Figs. S16 and S19), and sleep-related measures (Figs. S17 and S20). Taken
413 together, the analyses suggest that cognitive and mental health differences are also associated with
414 differences in the dynamics of physical health measures.

415 Discussion

416 After collecting a year's worth of fitness-tracking data from each of 113 participants, we ran each
417 participant in a battery of memory tasks and had them fill out a series of demographic and mental
418 health-related questions. We found that the associations between fitness-related activities, memory
419 performance, and mental health are complex. For example, participants who tended to engage in
420 a particular intensity of physical activity also tended to perform better on some memory tasks but
421 worse on others. This suggests that engaging in one form or intensity of physical activity will not
422 necessarily affect all aspects of cognitive or mental health equally (or in the same direction).

423 A number of prior studies have shown that engaging in exercise can improve cognitive and
424 mental health [2, 3, 4, 6, 10, 11, 12, 14, 25, 26, 27, 31, 33, 40]. The majority of these studies ask
425 participants in an "exercise intervention" condition (where participants engage in a designated
426 physical activity or training regimen) or a "control" condition (where participants do not engage in
427 the designated activity or training) to perform cognitive tasks or undergo mental health screening.
428 In other words, most primary studies treat "physical activity" as a binary variable that either is
429 or is not present for each participant. Most prior studies also track or manipulate exercise over
430 relatively short durations (typically on the order of days or weeks). Our current work indicates that
431 the true relations between physical activity, cognitive performance, and mental health may be non-
432 monotonic and heterogeneous across activities, tasks, and mental health measures. These relations
433 can also unfold over much longer timescales than have been previously identified (on the order
434 of months; Fig. 6). However, despite the complexities of the structures of these associations, we

435 also found that they were often remarkably consistent across people. For example, as displayed
436 in Figures 5 and S14, many of the associations between fitness, behavioral, and mental health
437 measures were consistent across over 97.5% of 10,000 randomly chosen subsets of participants.

438 One important limitation of our study is that we cannot distinguish correlations between
439 different measures from potential causal effects. For example, we cannot know (from our study)
440 whether engaging in particular forms of physical activity *causes* changes in memory performance
441 or mental health, or whether (alternatively) people who tend to engage in similar forms of physical
442 activity also happen to exhibit similar memory and/or mental health profiles. In other words, an
443 overlapping set of processes or person-specific attributes may lead someone to both form particular
444 habits around physical activity and display high or low performance on a given memory test. We
445 do not know whether memory performance or aspects of mental health might be manipulated
446 or influenced by changing the patterns of physical activity someone engages in. For this reason,
447 we have been careful to frame our findings as correlations and associations, rather than to imply
448 knowledge about a causal direction of our findings.

449 Although the present study cannot reveal causal effects, a large prior literature provides some
450 insight into potential causal effects by examining the neural and cognitive effects of a variety of
451 exercise interventions [5, 16, 19, 38, 39, 41, 42]. A limitation of that prior work is that most of
452 these studies examine how relatively short-term changes in physical activity (e.g., on timescales of
453 hours to days or, rarely, weeks to months) affect a cognitive performance on single task or aspect
454 of mental health. The present study examines longer-term physical activity (over a full year), and
455 relates long-term physical activity history to performance on a variety of tasks and to a variety of
456 mental health dimensions.

457 To the extent that physical activity *does* provide a non-invasive means of manipulating cog-
458 nitive performance and mental health, our work may have exciting implications for cognitive
459 enhancement. For example, one might imagine building a recommendation system that suggests
460 a particular physical activity regimen tailored to improve a specific aspect of an individual's cog-
461 nitive performance (e.g., the efficacy of a student's study session for an upcoming exam) or mental
462 health (e.g., reducing symptoms of anxiety before an important meeting). Just as strength training

⁴⁶³ may be customized to target a specific muscle group, or to improve performance on a specific
⁴⁶⁴ physical task, similar principles might also be applied to target specific improvements in cognitive
⁴⁶⁵ fitness and mental health.

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⁴⁷² helped to inspire the theoretical foundations of this work. Dave served as a mentor and colleague
⁴⁷³ on the project prior to his passing.

⁴⁷⁴ Data and code availability

⁴⁷⁵ All analysis code and data used in the present manuscript may be found [here](#).

⁴⁷⁶ Author contributions

⁴⁷⁷ Concept: J.R.M. and G.M.N. Experiment implementation and data collection: G.M.N. Analyses:
⁴⁷⁸ J.R.M., G.M.N., E.C., and P.C.F. Writing: J.R.M. with input from all authors.

⁴⁷⁹ Competing interests

⁴⁸⁰ The authors declare no competing interests.

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